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Update on Risk Reduction Activities for a Liquid Advanced Booster for NASA's Space Launch System

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Overview and Introduction to ABEDRR

- **Goals of NASA's Advanced Booster Engineering Demonstration and/or Risk Reduction (ABEDRR) are to:**
  - Reduce risks leading to an affordable Advanced Booster that meets the evolved capabilities of SLS
  - Enable competition by mitigating targeted Advanced Booster risks to enhance SLS affordability
- **SLS Block 1 vehicle is being designed to carry 70 mT to LEO**
  - Uses two five-segment solid rocket boosters (SRBs) similar to the boosters that helped power the space shuttle to orbit
- **Evolved 130 mT payload class rocket requires an advanced booster with more thrust than any existing U.S. liquid- or solid-fueled boosters**

ABEDRR Awards

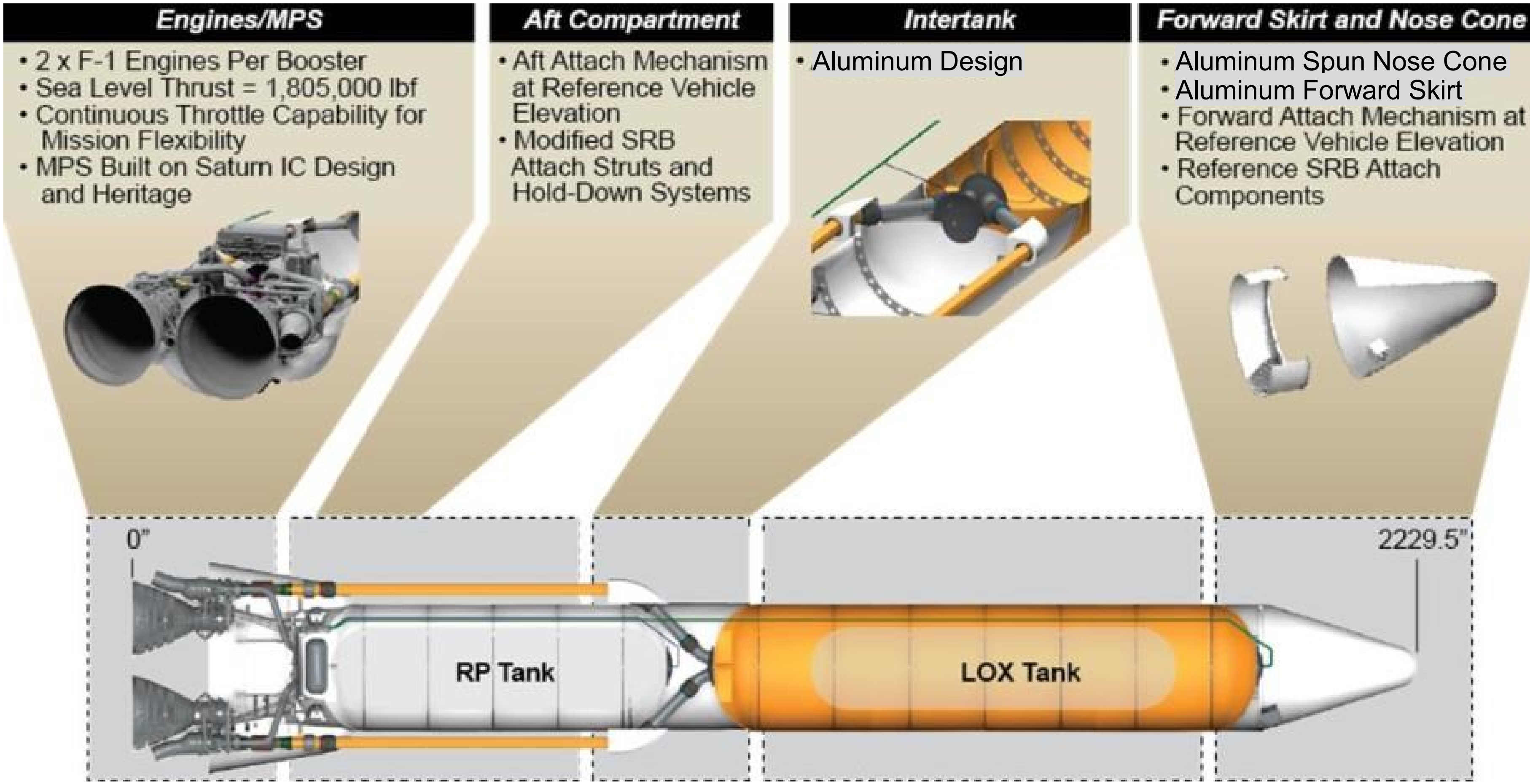
- **In October 2012 and February 2013, NASA awarded four contracts to improve the affordability, reliability, and performance of an Advanced Booster for the SLS:**
  - **ATK to demo innovations for advanced solid-fueled booster: composite case, propellant, nozzle, and avionics**
  - **NGC for design and mfg for composite propellant tanks**
  - **Aerojet Rocketdyne to improve the technical maturation of LOX/RP oxidizer-rich staged-combustion cycle engine**
  - **Dynetics, Inc. (with Aerojet Rocketdyne):**
    - **To demo the use of modern manufacturing techniques to produce and test several primary components of the F-1 rocket engine originally developed for the Apollo Program, including an integrated powerpack**
    - **To demo innovative fab techniques for metallic cryo tanks**

Scope of This Presentation

- **Early 2014, NASA and Dynetics agreed to move additional large liquid oxygen/kerosene engine work under Dynetics**
  - Originally had been its own ABEDRR prime contract to Aerojet
- **Led by Aerojet Rocketdyne, work is focused on an Oxidizer-Rich Staged Combustion (ORSC) cycle engine**
  - Can apply to both NASA's Advanced Booster and other launch vehicle applications, including Atlas V booster engine
  - Effort will demonstrate combustion stability and performance of a full-scale ORSC cycle main injector and chamber

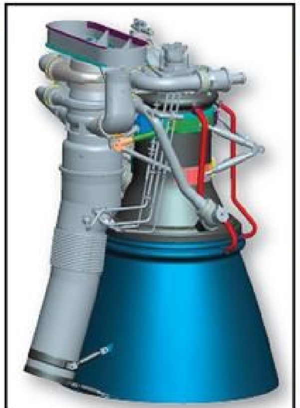
- **This presentation will discuss the Dynetics ABEDRR engine task (both efforts) and structures task achievements to date**

Original Dynetics Booster Configuration



Dynetics Risk Reduction Task Summary

A



B

A

Engineering Demonstrations and Risk Reduction Tasks	*Benefit of Proposed Effort/Status at Start of DDT&E*
F-1B Engine Risk Reduction	
Aerojet Rocketdyne Lead	
• Gas Generator Build and Test	• Full-Scale, Low-Cost, Production-Like, Throttling GG Hot-Fired
• Turbopump Build	• Full-Scale, Low-Cost, Production-Like, Throttling TPA Built
• Powerpack Build and Test	• Full-Scale, Low-Cost, Production-Like, Throttling PPA Hot-Fired
• Thrust Chamber Assembly Design and Build	• Full-Scale, Low-Cost, Production-Like, HIP-Bonded TCA Demonstrated
Structures Risk Reduction	
Dynetics Lead	
• Cryotank Assembly Build	• Full-Scale 18-ft Diameter Flight-Like Tank and Intertank Verified
• Cryotank Proof and Thermal Cycle	• Full-Scale Design,Tooling, and Build Processes Verified
ORSC Cycle Engine Risk Reduction	
Aerojet Rocketdyne Lead	
• Main Injector and Thrust Chamber Assembly Design, Build, and Test	• Full-Scale Demonstration of Combustion Stability and Performance Measurement

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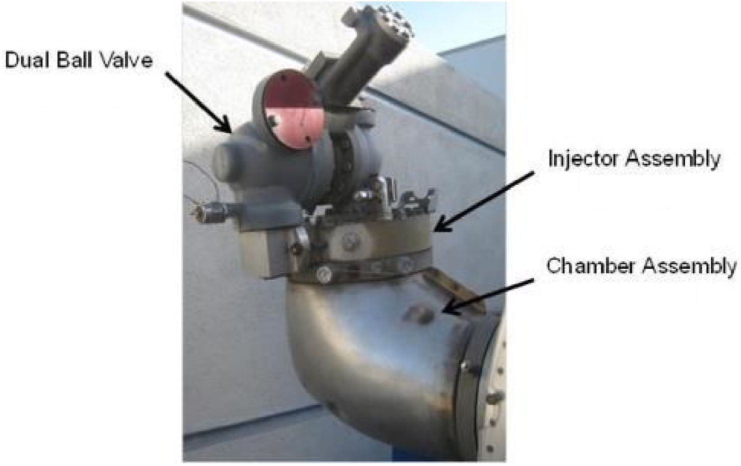
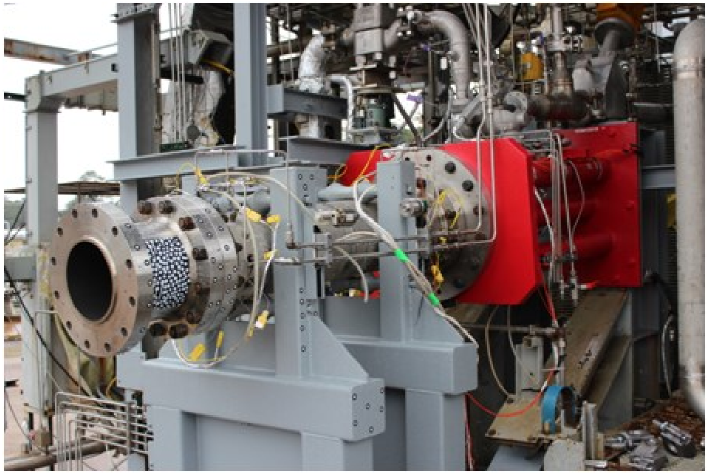
Heritage F-1 Gas Generator (GG) Testing

- **A GG test program was used to demonstrate continuous throttling, which offers SLS mission trajectory flexibility**
- **To enable early testing, existing GG and GG valve assets from heritage F-1 flight engines were used**
- **Primary test objectives were:**
  - **To verify performance and stability characteristics for the GG at heritage F-1A conditions**
  - **To verify performance and stability at throttled set points**
  - **To determine the thermal characteristics of the GG**



F-1 gas generator mounted at MSFC Test Stand 116



Heritage F-1 Gas Generator Testing (cont'd)

- **In February and March 2013, 10 tests were completed**
  - Seven were 20-second steady state tests at various chamber pressure and mixture ratio variations
  - One was a 35-second mainstage test
  - One was a 55-second, long duration mainstage test
- **Performance on all tests was nominal, and all test objectives were satisfied**
  - The test series verified the GG was stable at all throttle operating points from 63% to 100% power levels (1.3Mlbf to 1.8Mlbf)
  - A full duration qualification test was completed
  - The thermal performance of the GG was characterized
  - All performance data was consistent with heritage operations

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Heritage F-1 Gas Generator Testing (cont’d)

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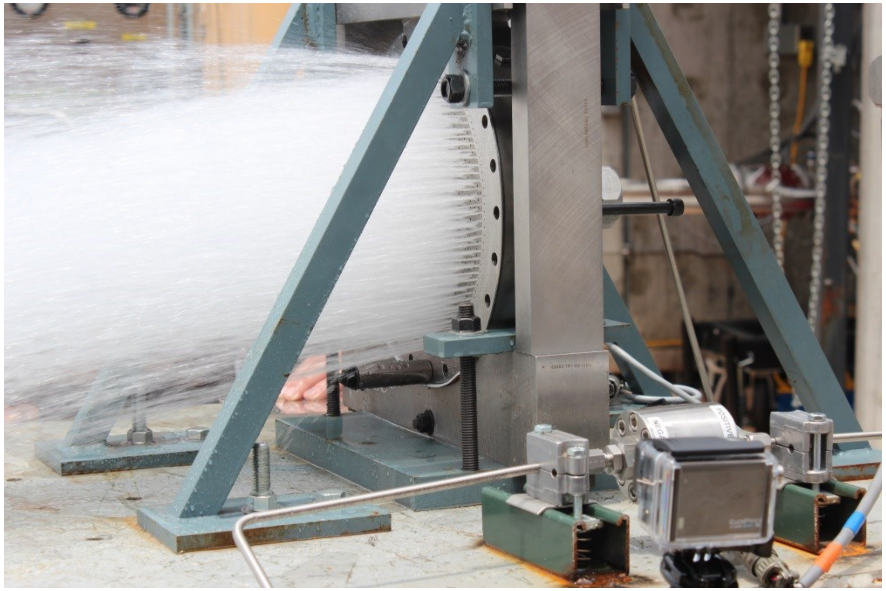
Additive Manufacturing of a F-1B GG Injector

- As a cost reduction opportunity, AR also fabricated a full-scale GG injector using a modern, low-cost, additive manufacturing technique called sintered laser melting (SLM)
- Proof testing and inspections were completed and passed
- In June 2014, NASA MSFC successfully conducted water flow testing of the injector to characterize the fuel and oxidizer flow passage resistances and visualize the flows
- Due to scheduling issues, hotfire testing of the SLM GG injector was delayed until September 2015



F-1B SLM GG injector flow calibration test

Testing an Additively Manufactured Injector

- Hotfire testing of the F-1B SLM GG injector was completed in the same MSFC test stand as the original heritage injector
- The main objective of the testing was to determine the combustion and stability characteristics and thermal performance of the injector manufactured with the SLM process
- All tests were successful and matched the heritage injector test results very well
- This test provided an opportunity for a one-on-one comparison of a part built with traditional manufacturing to a part built with a new process that the aerospace industry is investigating

F-1B SLM GG injector hotfire test at NASA MSFC

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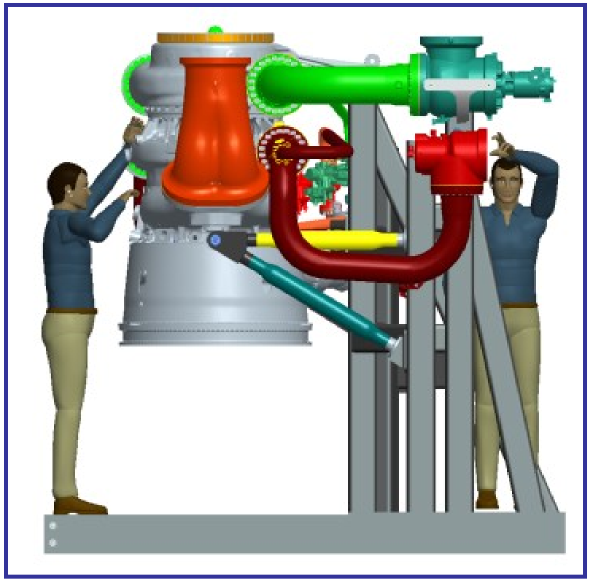
F-1B Risk Reduction – Previously Discussed

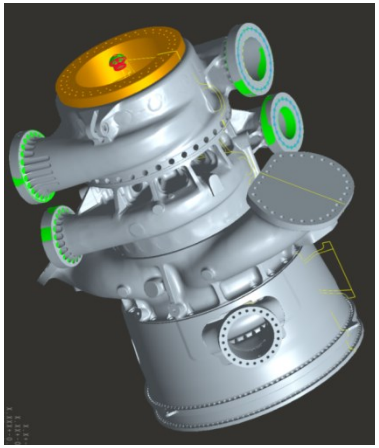
- This presentation will briefly discuss these activities, but they have been covered in detail in a previous paper/presentation

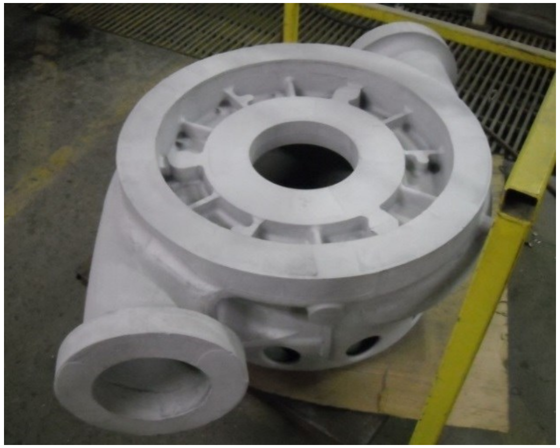
Structured light scanning the Mk-10A fuel inlet



Powerpack Assembly mounted on test skid

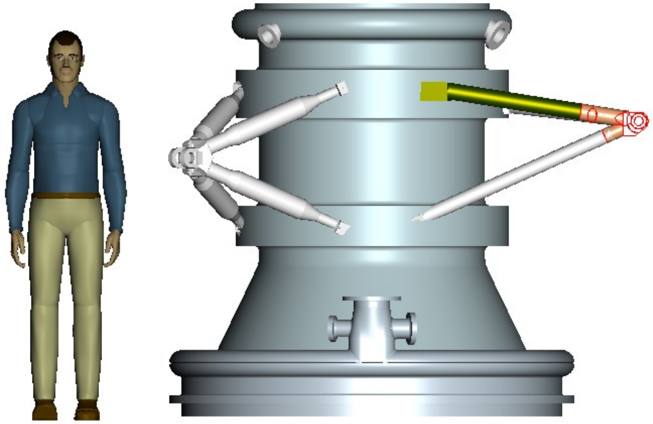
3-D Pro/Engineer turbopump assembly model created from scanned images





Successful F-1B LOX volute sand casting

F-1B Main Combustion Chamber



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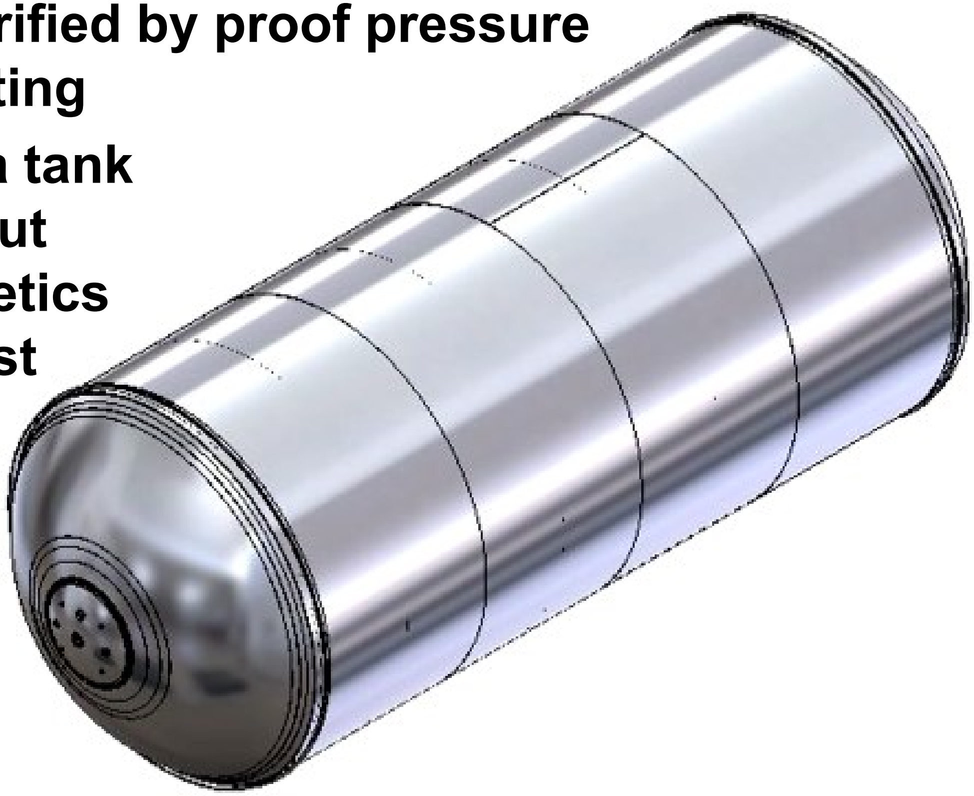
Overall F-1B Engine Risk Reduction Summary

- **Program objective was to reduce F-1B engine development risks—despite funding challenges, the effort met this objective:**
  - Demonstrated F-1B engine and component understanding and readiness
  - Completed a GG hot-fire test series, proving throttling capability
  - Completed a SLM hot-fire test series, proving similarity to heritage
  - Disassembled and reverse engineered existing Mk-10A turbopump
  - Demonstrated long-term affordability through full-scale demonstrations of an additively manufactured GG injector and a cast LOX volute, turbine blades, and turbine manifold
  - Prepared main propellant valves for test
  - Integrated engine loads and design, developed transient operational models, and designed interfaces with the facility for Powerpack testing
  - Developed a new MCC design focused on dramatic cost reductions

Structures Risk Reduction – Cryotank Build

- **Structures risk reduction task planned to validate the designs, materials, equipment, and processes to produce robust and affordable structures**
- **Ultimately, the task planned to create a full-scale cryotank assembly that would be verified by proof pressure and cryo-thermal cycle testing**
- **Original plan was to build a tank with four barrel sections, but NASA negotiated with Dynetics to reduce schedule and cost by building a tank with a single cylindrical barrel**
  - **Circumferential welding still demonstrated, and testing still completed**

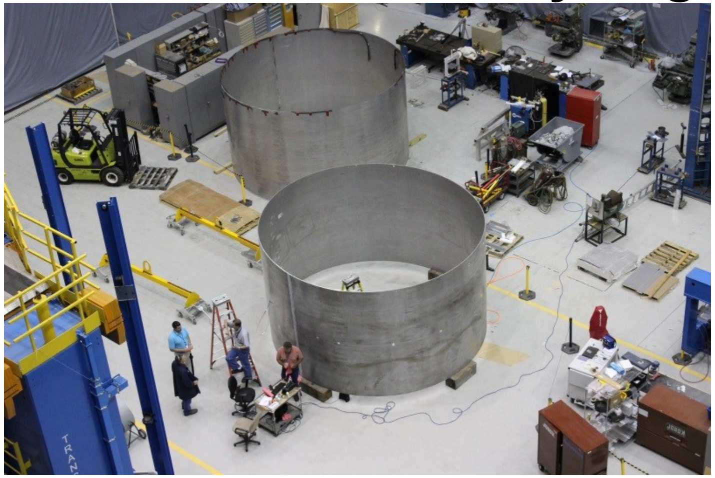


Structures Risk Reduction – Design and Analysis

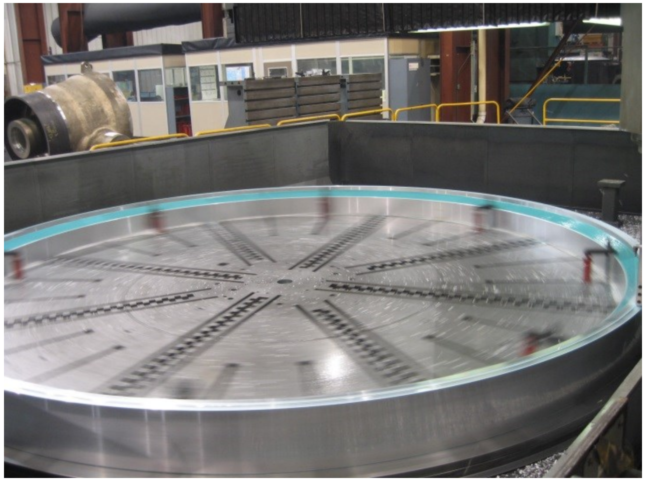
- Performed initial structural analysis and verified that the RP-1 tank, intertank, and LOX tank designs had positive margin for stress and buckling
- Performed detailed coupled loads analysis, including simulations for vehicle rollout, pre-launch, liftoff, and ascent phases (transonic, max Q-alpha, max Q, max thrust, and max acceleration), to generate the design loads
- Generated max shear and moment loads and Peq loads, interface loads, vehicle support post loads, and stay loads
- Generated fatigue and fracture stress spectra
- Working with NASA Langley, used the latest experimental data to update shell buckling knockdown factors
- Performed thermal analysis of the tanks and intertank
- Determined appropriate proof pressure levels for planned tank testing

Structures Risk Reduction – Barrel and Y-Ring Mfg

- Fabrication activities started with a mill run of Al 2219 plate
- Plates delivered to Spincraft for spin-forming domes and to Major Tool and Machine for manufacturing tank barrels
- Unique single-sheet barrel rolling technique was developed for the robust tank structure and demonstrated on 7 barrels
- ATI Ladish started with large aluminum ingots and worked them into ring forgings—sent to Major Tool and Machine to be machined into y-rings



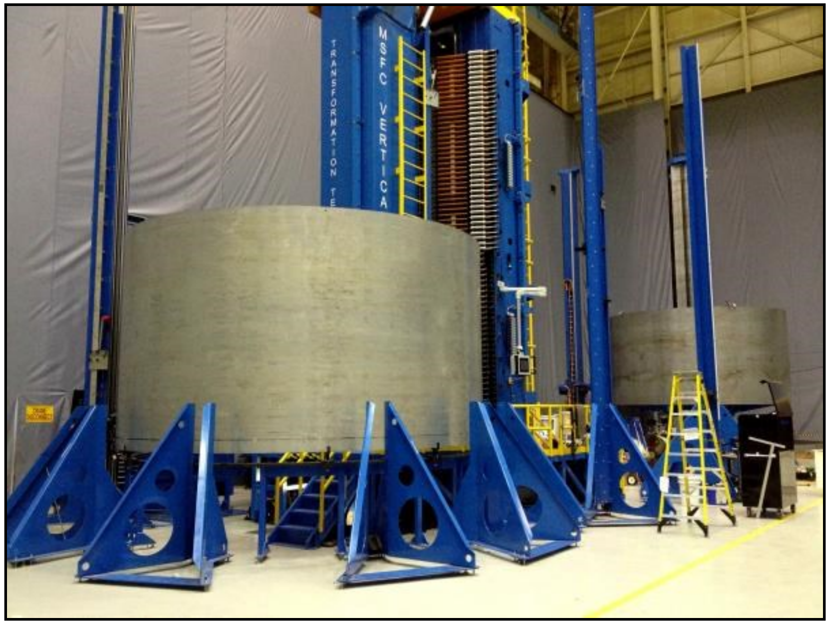
Dynetics tank barrels at NASA MSFC Building 4755



Dynetics y-ring in machining

Structures Risk Reduction – Tank Barrel Welding

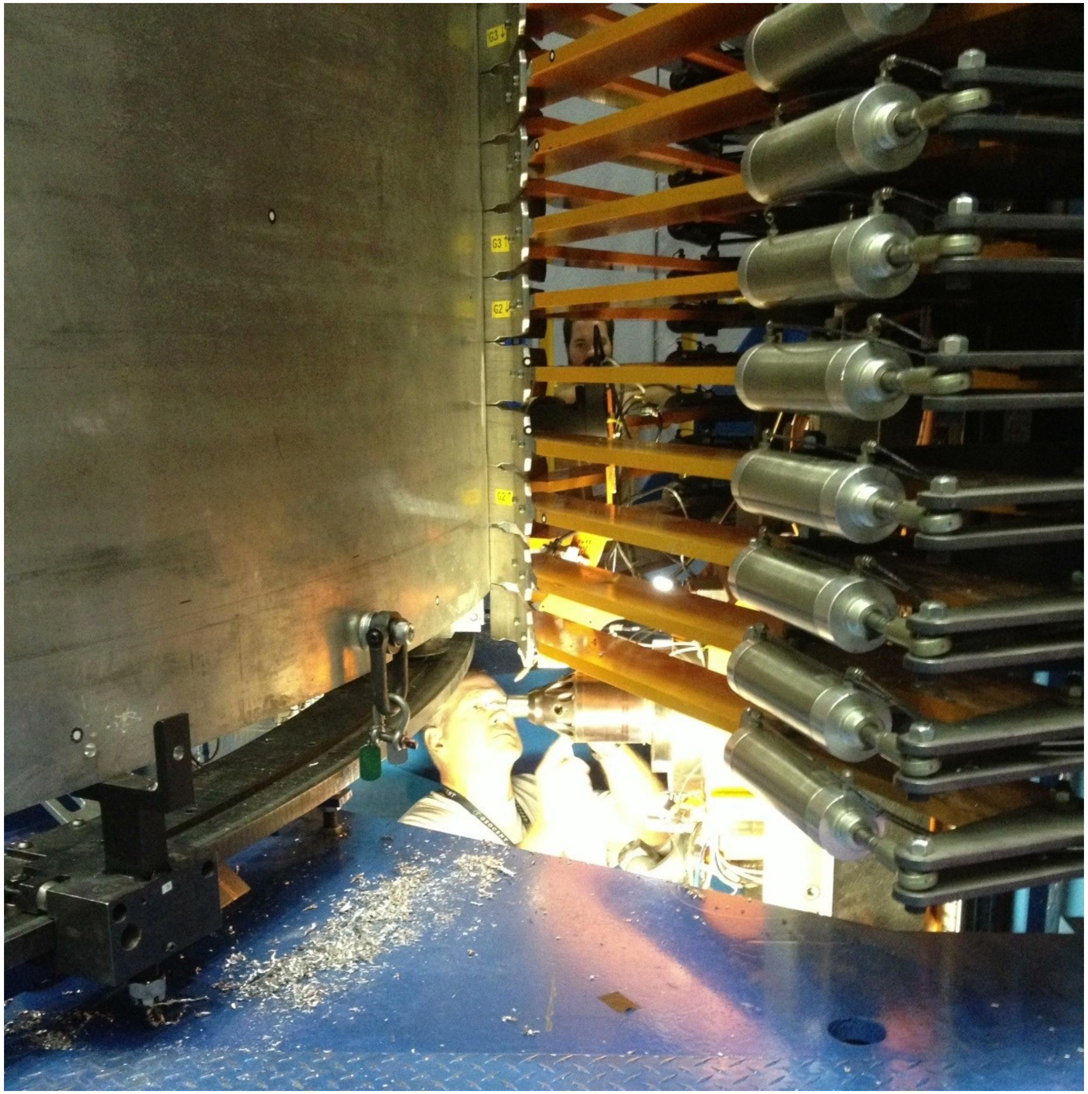
- **Developed a tank build plan to weld the barrels using NASA MSFC Friction Stir Welding (FSW) tools**
- **Developed conventional FSW parameters—implemented on longitudinal barrel welds on the Vertical Weld Tool**
- **All barrels passed Phased Array Ultrasonic Testing (PAUT) and dye penetrant testing**



Dynetics barrels on MSFC FSW tools, Vertical Weld Tool (near) and Vertical Trim Tool (far)

Structures Risk Reduction – Barrel Welding (cont'd)

Dynetics barrel on the
Vertical Weld Tool



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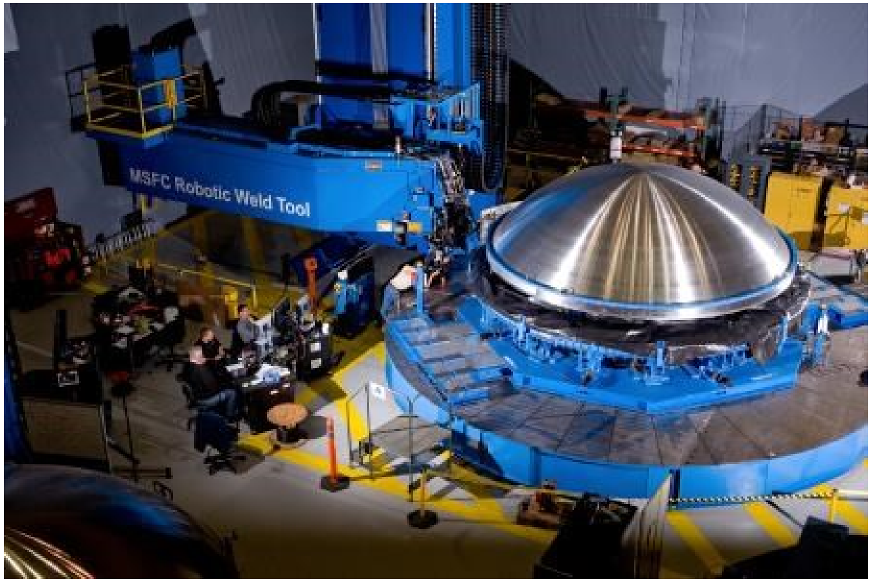
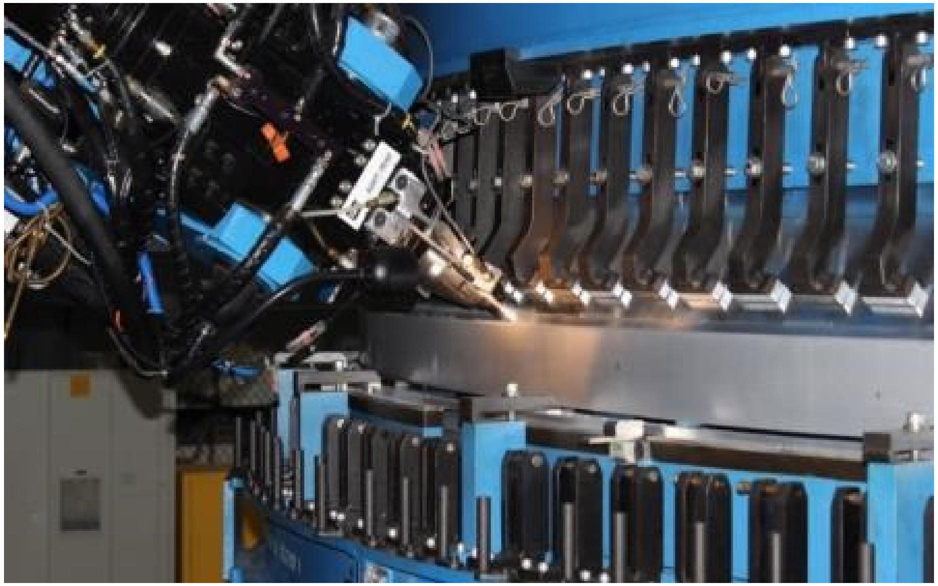
Structures Risk Reduction – Dome to Y-Ring Welding

- Developed weld schedule for self-reacting FSW
- Completed circumferential welding of two domes to y-rings on MSFC's Robotic Weld Tool
- Passed PAUT and dye penetrant testing



Tank dome on the MSFC Robotic Weld Tool



MSFC RWT welding Dynetics dome to y-ring

Structures Risk Reduction – Dome to Barrel Welding

- Developed weld schedule for self-reacting FSW for circumferentially welding tank barrels to the dome/y-ring assemblies and the barrels to other barrels on MSFC's Vertical Assembly Tool
- Mechanical modifications were made to the tool to accommodate the size and weight of Dynetics' structure
- Test welds were completed; all passed PAUT inspection, tensile testing results good
- Next step to complete final circumferential welds

NASA MSFC's Vertical Assembly Tool

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Structures Risk Reduction – Final Tank Welding

- **Circumferential welding started with the aft end of the tank**
  - Hawthorne clamps used to hold the y-ring and barrel together for welding
- **PAUT inspection completed**
  - One defect found in overlap region of weld
  - Created a defect panel with a similar sized indication, tensile tested, resulted in a weld strength higher than the design allowable
- **Forward end welded with same approach**
- **PAUT inspection completed**
  - Tiny indications found at notches for Hawthorne clamps
  - Indications measured, sum of all was much smaller than aft end weld indication
- **All welds deemed acceptable**

Finished Tank

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Structures Risk Reduction – Test Article Integration

- **Tank, test stand, and supporting hardware moved from MSFC fab facilities to test site in Iuka, MS**
- **Once in Iuka, tank integrated to test stand to form the test article**
- **Strain gauges installed on test article**
- **After strain gauge installation, test article transported to test pad**
- **Once mounted to test pad, modified lifting fixture with decking installed**

Integrating the tank and test stand in Iuka, MS

Placing the integrated test article on the test pad

Structures Risk Reduction – Testing Introduction

- Dynetics performed series of proof and thermal cycle tests
- Demonstrates that designs, materials, manufacturing processes, and inspection methods for building pressurized cryotanks are ready for DDT&E

- Testing conducted per a NASA-approved test matrix
- Test pass/fail criteria were defined in a Tank Test Plan
- Procedures generated to define the steps for each test

Structures Risk Reduction – Hydrostatic Proof Testing

Test 1 – Hydrostatic Proof Test

- Test article was 100% filled with water
- Pressurized with GN_2 to 10 psig ± 2 psi to verify strain gauges operational
- Tank pressurized to specified hold points, held for 3 mins each
- Pressurized to target pressure, held for 5 mins

- All strain, temperature, and pressure sensors operational
- Visual leak checks performed throughout the test
- Test was a success; strains observed were in ranges expected

- Following tank drain, sump seals replaced with cryogenically-rated Chrysler O-ring seals; tank reassembled per cryogenic configurations defined in Test Plan

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Structures Risk Reduction – Cryothermal Testing

Test 2 – LN_2 Transfer and Control Test

Chilling test stand with LN_2

- Purpose was to serve as a trial run for test team operations and provide opportunity to test fill, vent, and drain
- Prior to test, test article was purged with GN_2 to remove/prevent moisture
- Filled tank with 6,000 gal of LN_2, bottom dome filled up to the aft y-ring
- After fill, controlled boil-off and pressurization
    - Max pressure reached less than 7 psig
- All measurements and visual results satisfactory
- Prior to next test, access ports on stand sealed with insulation
- Also added LN_2 sprinkler to chill stand faster to reduce the temperature delta between the stand and tank y-ring interface

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Structures Risk Reduction – Cryothermal Testing (cont'd)

Test 3 – Cryothermal Cycle / Proof Test

- **Only issue was failure of LN_2 fill isolation valve**
  - Valve was manually opened to avoid problems
  - Total fill operation took approximately 12 hours
- **When tank approximately 95% full, all tank valves closed, and tank was pressurized with GHe**
  - Target pressure was held for 5 mins
- **Used temp-compensating thermocouples and low-temp strain gages**
- **Test was successful**
  - Reached target pressure
  - All measurements and visual results were satisfactory
  - No yielding of tank structure

Integrated test article chilled with LN_2

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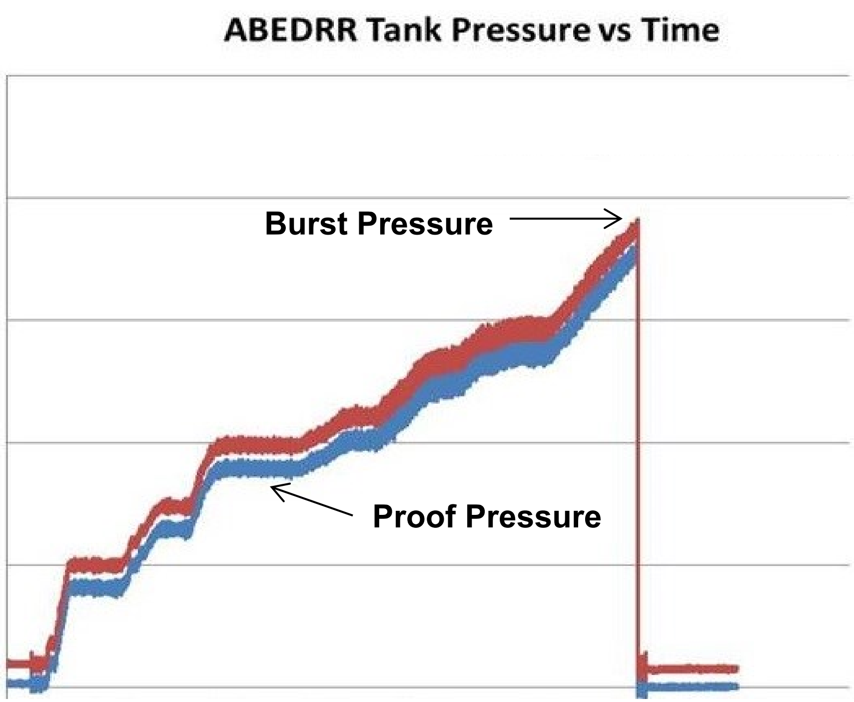
Structures Risk Reduction – Hydrostatic Burst Testing

Test 4 – Hydrostatic Proof / Burst Test

- **Test article 100% filled with water**
- **Tank hydrostatically pressurized using a water pump**
- **Pressure points held for 3 mins each**
- **Failure location at machining non-conformance on the top dome**
- **Test was successful**
  - Met previous proof pressure
  - Burst pressure >2x proof
  - All measurements and visual results were satisfactory
- **Proof and burst test results verified structural design and manufacture of an affordable booster concept for the SLS**



Structures Risk Reduction – Burst Testing (cont'd)

Moments after tank burst

Several seconds after tank burst

ORSC Cycle Engine Risk Reduction

- Effort focused on design, analysis, fab, and test of 500 klbf full-scale ORSC main injector, TCA, and supporting hardware
- Test article scheduled to complete critical design review in Fall 2015, begin testing in early 2017
- Following activities have been accomplished:
  - Main injector and TCA made design and analysis progress, incl several design reviews, and completed fab risk reduction activities
  - Integrating components completed CDR, begun long-lead fab
  - Requirements dev, prelim design for test skid
  - Design reviews, long-lead procurements for NASA SSC test facility
- In the coming months, the team will:
  - Complete injector and TCA design and analysis, proceed into fab
  - Complete fab of integrating components
  - Finalize design and build test skid, test facility
  - Conduct testing of injector and TCA to demo combustion stability

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Summary

- AR has applied state-of-the-art manufacturing and processing techniques to the heritage F-1, resulting in many noteworthy accomplishments and reducing the risk for full-scale engine development
- AR has also made progress on technology demonstrations for ORSC cycle engine, which offers affordability and performance for both NASA and other launch vehicles
- Dynetics has designed innovative tank and structure assemblies; manufactured them using FSW to leverage NASA investments in tools, facilities, and processes; conducted proof and burst testing, demonstrating the viability of design and build processes